VALIDATION OF COASTAL SEA AND LAKE SURFACE TEMPERATURE MEASUREMENTS DERIVED FROM NOAA/AVHRR DATA

Xiaofeng Li, W. Pichel*, P. Clemente-Colón*, V. Krasnopolsky**, and J. Sapper*

Research and Data Systems Corporation
Room 102, NOAA Science Center 5200 Auth Road, Camp Springs, Maryland 20746, U.S.A.

*NOAA/NESDIS, Room 102 NSC, Mail Stop 9910, 4700 Silver Hill Rd.,
Washington, D.C. 20233-9910, U.S.A.

**General Sciences Corporation
6100 Chevy Chase Dr., Laurel, Maryland, 20707, U.S.A

ABSTRACT

An interactive validation monitoring system is being used at NOAA National Environmental Satellite, Data and Information Service (NESDIS) to validate the sea surface temperature (SST) derived from the NOAA 12 and NOAA 14 polar orbiting satellite AVHRR sensors for the NOAA CoastWatch program. In 1997, we validated the SST in the coastal regions of the Gulf of Mexico (GM), Southeast US (SE) and Northeast US (NE) and the lake surface temperature in the Great Lakes (GL) every other month. The *in situ* temperatures measured by twenty-five NOAA moored buoys are used as ground truth. The non-linear algorithm (NLSST) is used for all AVHRR SST estimation except during the day in the GL where the linear multi-channel SST (MCSST) algorithm is used. The buoy-satellite match-up is made within one image pixel in space (1.2 km at nadir) and within one hour in time.

For the NOAA-12 satellite, there are total of 679 matches in the three coastal regions (GM, SE and NE). The mean difference between satellite and buoy surface temperature (ΔT) matches is less than 0.50°C with a standard deviation of about 1.0°C. In the GL region, ΔT is 0.26°C during the day with a standard deviation of 0.83°C. The NOAA-12 night algorithm in the GL region generates a large bias of 1.52°C (82 matches).

The same statistics have been computed for NOAA-14 satellite measurements. For the coastal regions, ΔT is more accurate than that of NOAA-12. The bias is less than 0.2°C during the day and less than 0.1°C at night (448 matches). The standard deviation is about 1.0°C. In the GL region; ΔT is about 0.4°C at night (372 matches) with a standard deviation of 1.0°C.

1. INTRODUCTION

To derive the Sea Surface Temperature (SST) from satellite measurements has been a focus of numerous studies since the earlier 1970's (Anding and Kauth, 1970; McMillin, 1975; Barton, 1983; Llewellyn-Jones 1984, McMillin and Crosby 1984, McClain et al. 1985, McMillin et al. 1985; Walton, 1988; Barton et al. 1989; Minnett, 1990; Emery et al. 1994, Walton et al. 1998). The Advanced Very High Resolution Radiometer (AVHRR/2) onboard the NOAA series of Polar-Orbiting Operational Environmental Satellites (POES) is primarily designed for SST retrieval and cloud detection. POES satellites known as Advanced Television Infrared Observation Satellites (TIROS-N or ATN) operate as a pair to ensure that the data, for any region of the earth, are no more than 6 hours old. AVHRR has

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five channels, two visible channels at 0.6 and 0.9 μm, one short-wavelength infrared channel at 3.7 μm, and two long-wavelength infrared split channels at 11, and 12 μm. The spectrum of the three infrared channels is selected in the band that the radiation from the Earth's or a cloud surface is weakly attenuated. To determine the actual SST from the AVHRR radiation measurements, one must correct for the absorption and emission of atmospheric radiation. The split window method, which uses the channel 4 and 5 brightness temperature to calculate SST, is widely used for atmospheric correction. A summary and comparison of different split window algorithms can be found in Barton (1995). Operational multichannel AVHRR SST algorithms have been used to generate the high resolution SST imagery at NOAA National Environmental Satellite, Data, and Information Service (NESDIS) since November 1990. CoastWatch was fully operational in 1992 with one satellite. The second satellite was added in 1994.

Based on the split window theory, Multichannel SST (MCSST) was developed and used operationally at NOAA/NESDIS for global SST measurements beginning in November 1981. This algorithm assumes that there is a linear relationship between the difference of actual SST and the satellite measurement in one channel and the difference of satellite measurements in the two split window channels (channels 4 and 5). Therefore, the actual SST can be estimated using brightness temperatures measured with Channels 4 and 5. Walton (1988) considered a non-linear term in the further development of the MCSST algorithm and developed the Cross Product SST (CPSST) algorithm. A simple version of the CPSST algorithm, the Non Linear SST (NLSST), was implemented at NOAA/NESDIS for operational use in March 1990. A more detailed discussion of the development of the NLSST algorithm can be found in Walton et al. (1998). The coefficients in these algorithms are routinely obtained by performing regression between satellite retrievals and global drifting buoy data soon after each satellite's launch. These coefficients vary from satellite to satellite, and for daytime and nighttime measurements.

The satellite derived SST imagery has been widely used in studying atmospheric and oceanic problems. For some research applications, relatively low absolute SST accuracy is required as long as high relative accuracy is achieved, i.e., front and edge detection (Cayula and Cornillon, 1992; Kahru et al., 1995), and feature tracking and motion detection (Emery et al. 1991; Breaker et al. 1994). However, in some other studies, i.e., climate studies (Harries et al., 1983), more stringent absolute SST accuracy, normally less than 0.3°C, is required. To understand the satellite derived SST accuracy, various validation efforts have been performed by comparing the AVHRR measurements with moored buoy, drifting buoy and ship measurements globally as well as in different coastal regions.

For the global validation, AVHRR Global Area Coverage (GAC) data with a spatial resolution of 9 km/pixel and 8 km SST observation is normally used. Pichel (1991) used three months of NOAA-14 satellite and buoy matchups data set between March and May 1990 to validate the NLSST algorithm, and found global biases (i.e., mean satellite – buoy difference) less than 0.3°C with a standard deviation of about 0.7°C. Walton et al. (1998) analyzed a nine-year time series of satellite-buoy matchup between 1989 and 1997. They showed that the bias has stayed between -0.2°C and 0.4°C over the nine year period, while the scatter (i.e., the standard deviation) of the difference between the satellite and buoy SSTs improved from 0.8°C to 0.5°C for the daytime algorithm but remained about 0.5°C for the nighttime algorithm. After the Mt. Pinatubo Eruption in October 1992, the resulting stratospheric volcanic aerosols caused a positive bias in the nighttime SST measurements until June 1993. The GAC SST buoy matches are made within 25 km and 3 hours.

There are a lot of factors controlling the accuracy of the AVHRR SST measurement, i.e., optical properties of atmosphere such as the injection of aerosols (McMillin and Crobsy, 1984), atmospheric profiles (Yokoyama and Tanba, 1991), and these factors vary from place to place. In addition, a matchup made within 3 hours in the GAC data validation can give wrong result when the diurnal effects are considered (Cornillion and Stramma, 1985 Hawkins et al. 1993). Therefore, it is important to understand how accurate the AVHRR SST algorithm is in different coastal regions. That validation needs a satellite-buoy matchup data set closer in space and time. There have been a number of studies concerning regional AVHRR SST validation. Pearce et al. (1989) validated NOAA-7 and NOAA-9 derived SST using *in situ* boat measurements as ground truth in the coastal waters off Western Australia. They compared seven published split window algorithms and found that all algorithms yielded reasonably good results. The RMS error between the SSTs derived with two appropriate algorithms and boat measurements is about 0.6°C. The bias is between -0.1°C and 0.2°C. Robinson and Ward (1989) compared Llewellyn-Jones (1984) split window algorithm SSTs with the cruise data in the north-east Atlantic Ocean for the NOAA-7 satellite. The ship and satellite measurement agreement is within 1°C. Yokoyama and Tanba (1991) compared fourteen published split window algorithms using a matchup data set in Mutsu Bay in northern Japan for the NOAA-9 satellite. They showed that the regional split window algorithm had RMS errors in the range of 0.55°C to 0.75°C. But the RMS errors of the published split window algorithms were between 0.56°C and 2.31°C. The significantly improved regional split window algorithm lead them to conclude that the split window algorithm should be calibrated by a regional matchup data set, because the split window algorithm coefficients were affected by regional atmospheric profiles. In their more recent paper, Yokoyama et al. (1993) found that larger satellite retrieval errors appeared to happen when the air sea temperature difference was large.

In this study, we use a long term validation system developed for the NOAA CoastWatch program to validate the AVHRR SST accuracy in the Northeast, Southeast, and Gulf of Mexico coastal regions and the lake surface temperature in the Great Lakes area for NOAA-12 and NOAA-14 in 1997. In section 2, CoastWatch AVHRR data preparation is presented followed by a description of the validation procedure description in Section 3. In Section 4, we present validation results. Analysis and discussion and conclusion are in Section 5.

2. NOAA COASTWATCH AVHRR DATA PREPARATION

2.1 Satellite mapped data for CoastWatch

Input data for the production of CoastWatch imagery are AVHRR High Resolution Picture Transmission (HRPT) 1b data sets. These consist of AVHRR detector output from the five channels of the AVHRR with appended calibration and earth location information. Data sets are received from every satellite pass over the Wallops Station, Virginia reception mask. Currently, NOAA-12 and NOAA-14 are the two operational satellites. NOAA-12 was launched on May 14, 1991, into a sun-synchronous polar orbit with equator crossing times early in the morning at 07:09 am descending and in the evening at 19:09 pm ascending. NOAA-14 was launched on December 30, 1994, into a similar orbit with equator crossing times ascending in the afternoon at 13:43 pm local time and descending at night at 01:43 am. NOAA-12 and NOAA-14 are designated as the operational morning and afternoon satellites, respectively. Usually, each CoastWatch region receives satellite coverage four times per day. Satellite data from Wallops are transmitted to the NESDIS Central Environmental Satellite Computer System (CEMSCS) as soon as each satellite overpass is completed. Processing into 1b data proceeds automatically as soon as the complete pass has arrived, followed by CoastWatch mapping over each region covered by the satellite pass.

2.2 CoastWatch mapping

The AVHRR NOAA level 1b data are mapped to Mercator projection "region" maps covering entire CoastWatch regions. All five channels, as well as the satellite and solar zenith angles, are mapped at 1.2 km resolution at nadir. The zenith angle is the angle at a point on the earth between the local normal at that point and a line connecting the point on the earth and the satellite or the sun. For NOAA POES satellites, the range of satellite zenith angle can be from 0° to 60°. If there is a significant variation in satellite height, the satellite zenith angles generated are expected to be off by 1% for every 50 km at high zenith angle. To prevent such large error from occurring at large satellite zenith angles, data with satellite zenith angle above 53 degree are flagged out in all of our validation regions except Gulf of Mexico.

2.3 Nonlinear SST (NLSST) and multi-channel SST (MCSST) algorithms

Once the data have been mapped, then the multiple channels and angles are combined with multi-channel algorithms to produce SST and cloud mask imagery. SST imagery is generated with the non-linear NLSST split window algorithm in the US coastal regions. This algorithm utilizes the difference between the 11 μm and 12 μm infrared channels to correct for the effects of water vapor. Since infrared radiation is absorbed by atmospheric moisture more at 12 μm than at 11 μm, the temperature difference between these channels is proportional to the amount of water vapor in the atmosphere. The equations also contain a correction for atmospheric path length variation with satellite zenith angle. The linear MCSST split window equation is used to obtain an estimate of the surface temperature for the non-linear term of the NLSST equation. Separate equations are used for day and night data and the equations are satellite dependent. These equations are generated after satellite launch by matching a month's worth of satellite data with global drifting buoy observations. All matches within 25 km and 3 hours are used in a regression analysis in order to derive the equations. Because of the global nature of the match data set, the regression equations are usually independent of season, geographic location, or atmospheric moisture content. However, adjustments to the equations have been necessary when instrument or spacecraft environmental changes have effected the calibration, and when volcanic stratospheric aerosols cover large regions of the Earth. The NLSST and MCSST equations are given below:

$$NLSST=A_1 (T_{11}) + A_2(T_{11}-T_{12})(MCSST) + A_3(T_{11}-T_{12})(Sec\theta - 1) - A_4 \quad (5)$$
$$MCSST= B_1 (T_{11}) + B_2(T_{11}-T_{12}) + B_3(T_{11}-T_{12})(Sec\theta -1) - B_4 \quad (6)$$

Where, T_{11} and T_{12} are the AVHRR 11 and 12 μm channel temperatures in Kelvin; $Sec\theta$ is the secant of the satellite zenith angle θ; NLSST and MCSST are the non-linear and linear multi-channel SST algorithms, respectively, in Centigrade; A_1-A_4 and B_1-B_4 are constant coefficients. A_1-A_4 and B_1-B_4 coefficients for NOAA-12 and NOAA-14 day and night algorithms are given in Table 1.

Table 1. NOAA 14 and NOAA 12 NLSST and MCSST algorithm coefficients

NLSST COEFFICIENTS					
		A_1	A_2	A_3	A_4
NOAA-14	DAY	0.939813	0.076066	0.801458	255.165
NOAA-14	NIGHT	0.933109	0.078095	0.738128	253.428
NOAA-12	DAY	0.876992	0.083132	0.349877	236.667
NOAA-12	NIGHT	0.888706	0.081646	0.576136	240.229
MCSST COEFFICIENTS					
		B_1	B_2	B_3	B_4
NOAA-14	DAY	1.017342	2.139588	0.779706	278.430
NOAA-14	NIGHT	1.029088	2.275385	0.752567	282.240
NOAA-12	DAY	0.963563	2.579211	0.242598	263.006
NOAA-12	NIGHT	0.967077	2.384376	0.480788	263.940

The CoastWatch equations differ from the global SST equations in three respects:

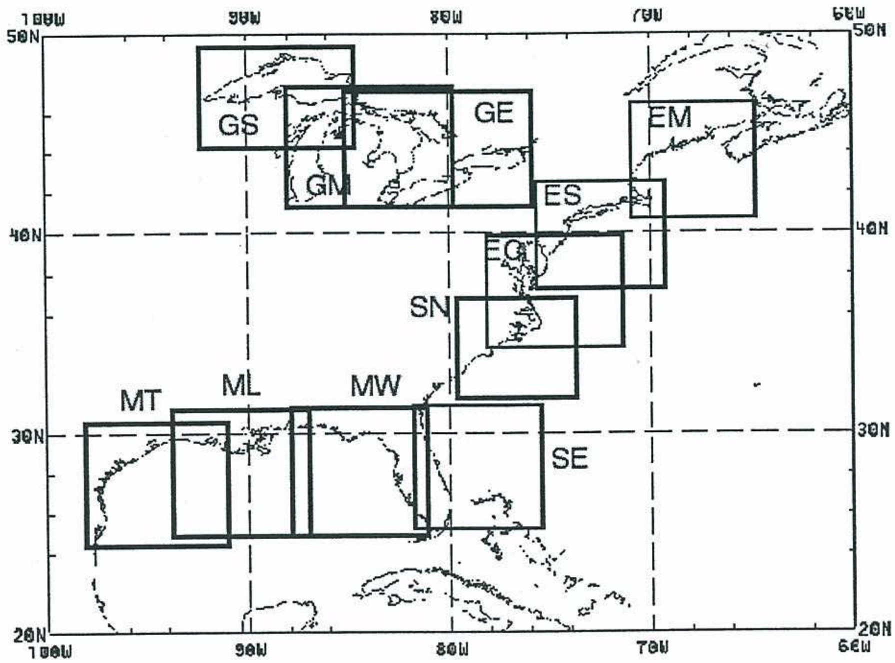
(1) The CoastWatch equations use the MCSST value in the non-linear term instead of a priori SST estimate obtained from an analysis of past satellite SST data (as is done in the global SST operation). This means that there is somewhat more noise in the CoastWatch observations. Both the global operation and CoastWatch constrain the value of the a priori SST or the MCSST to the range 0°C to 28°C.
(2) In the Great Lakes, the MCSST value is used as the final SST value during the day; i.e., a linear equation is used as the operational equation rather than a non-linear equation.
(3) The NLSST split-window equation is used for CoastWatch rather than the triple-window equation (which employs all three infrared channels) used in the global operation. For NOAA-12, the 3.7 μm channel is not used for CoastWatch because there is a problem in the calibration of that channel during part of each orbit. For consistency, the NLSST split-window equation is also used for the NOAA-14 CoastWatch equations.

2.4 CoastWatch image product

Once SSTs are generated by the NLSST and MCSST algorithms, the CoastWatch mapping system generates a series of "sector" images from the region maps. These sector maps are all 512 × 512 pixels in size for selected areas within the region. Sectors are produced at full-resolution for the validation areas shown in Fig. 1. A 512 × 512 "synoptic" image is also produced from the region map by taking every other or every third image row and column. This synoptic image then depicts the entire region at reduced resolution. Sector maps can be IR or visible channels, angles, SST, or cloud masks. All the sector products as well as the full-resolution region maps are now being archived. In this study, we use the full resolution images to validation the AVHRR SST product.

Fig. 1 CoastWatch High Resolution AVHRR Data Areas

Great Lake:	Lake Huron, Erie & Ontario (GE); Lake Michigan & Huron (GM); Lake Superior (GS)
Northeast:	Chesapeake Bay (EC); Gulf of Maine (EM); Southern New England (ES)
Southeast:	East Florida (SE); North Carolina (SN)
Gulf of Mexico:	Louisiana and Mississippi (ML); Texas (MT); West Florida (MW)



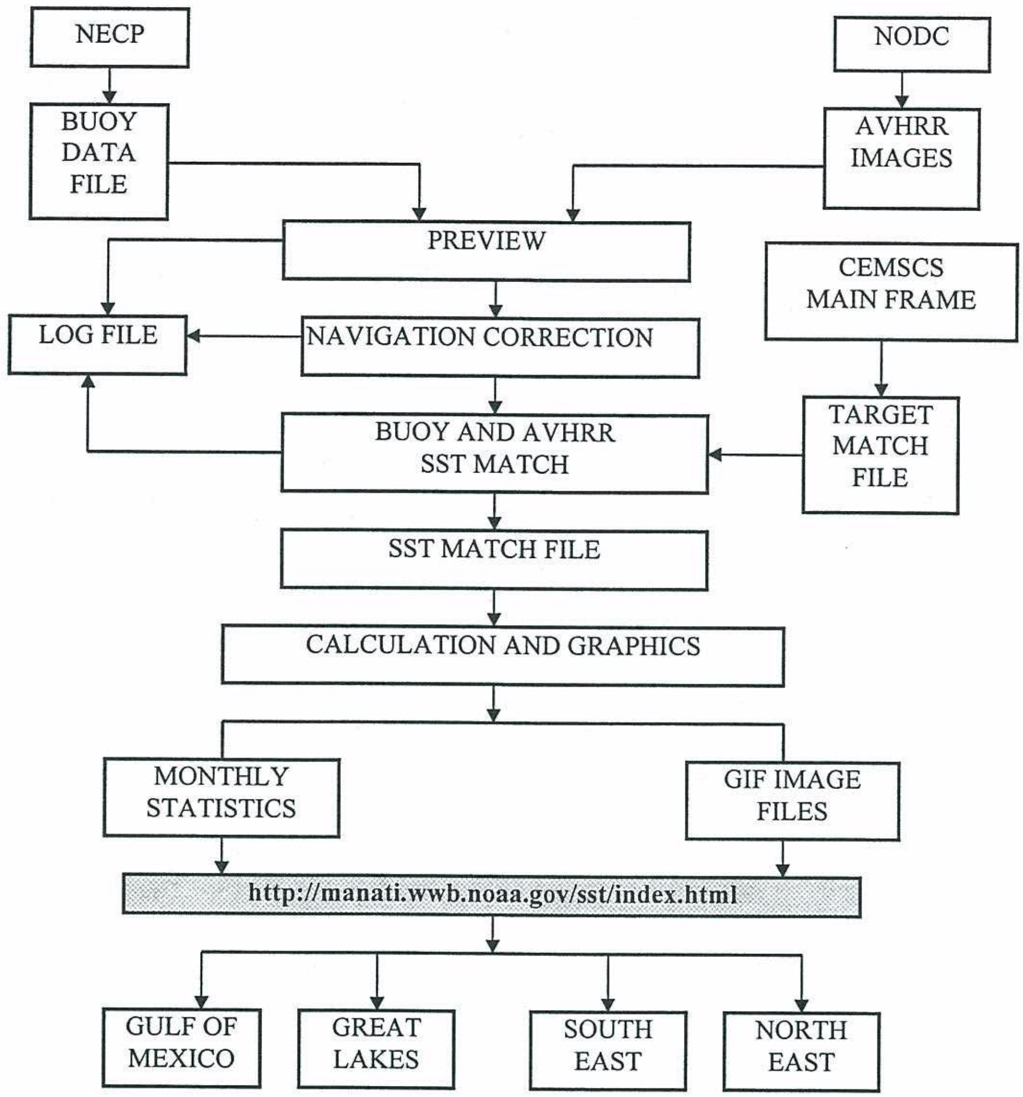
A cloud-mask image product useful for interpretation of the SST imagery or for automatic multi-day composting of cloud-free pixels is also generated. The algorithm employed is the Clouds from AVHRR (CLAVR) algorithm (Stowe, et al., 1991). With a series of threshold, uniformity, and channel difference or ratio tests, the CLAVR algorithm determines whether each 2 × 2 pixels array in the region map is clear or cloudy. The cloud maps are generated in the same projection as these of the SST images. The satellite navigation error is corrected in the following validation system, not in the original NOAA level 1b data process.

3. NOAA COASTWATCH VALIDATION PROCEDURE

The CoastWatch validation system is an interactive, menu driven, image and data processing system. The system is developed using IDL computer language and can be run on both VAX and UNIX platforms. This system is designed in order to provide long-term validation for the CoastWatch SST, visible and cloud-mask imagery. The hierarchy chart of the current validation system is presented in Fig. 2.

The NOAA National Center for Environmental Predication (NECP) provides data for the buoy data file by obtaining the entire moored buoy reports during fixed six-hour time periods. This file is updated four times a day. The buoy data file also gives the current NOAA moored buoy locations, so an analyst can overlay the buoys on the AVHRR

Fig. 2 NOAA CoastWatch long term AVHRR SST validation system



imagery. AVHRR imagery is in the CoastWatch format and images are archived at the National Oceanographic Data Center (NODC). The input to the long-term validation system is the Target Match File (TMF). The TMF is generated by extracting 15×15 pixel array targets of AVHRR imagery centered at NOAA moored buoy positions.

The long-term validation system enables an analyst to: (1) preview AVHRR images (both infrared and visible channels). The accuracy of CoastWatch SST products for each new satellite is assessed after the initial global equations are generated and before declaring the new satellite as operational for CoastWatch. (2) overlay maps, buoy and AVHRR imagery header information on the images, (3) renavigate the imagery by shifting the image to agree with superimposed coastlines (Krasnopolsky and Breaker, 1994), (4) display cloud masks, (5) extract from the TMF clear 3 × 3 arrays of CoastWatch SST values from the closest pixel to the position of all the buoys in each coastal region, (6) create an output SST match file which contains satellite and buoy SSTs, air temperature, wind and wave information, solar and satellite zenith angles, and navigation information, (7) calculate statistics.

4. VALIDATION RESULTS

In 1997, the validation is performed in the US GM, SE, and NE coastal region as well as in the GL region every other month. Both NOAA-12 and NOAA-14 satellite images are validated. The mean and standard deviation of extracted 3 × 3 arrays from CoastWatch SST imagery are calculated and stored in the SST match files. We use the center point of this 3 × 3 array as the satellite measurement. There are a total of 1829 matchups in the three coastal regions, and 693 matchups in the Great Lakes. The Great Lakes matchups are usually not available in the winter when the buoys are removed to prevent ice damage. In this study, the Great Lakes matchup data set in May, July, and September 1997 is included.

Table 2. Mean satellite-buoy SST difference (bias) and standard deviation for NOAA-12 and NOAA-14

CoastWatch Northeast, Southeast, and Gulf of Mexico Regions					
Satellite	Time	Algorithm	Number of Matches	(Satellite-Buoy) SST	Standard Deviation
NOAA-14	DAY	NLSST	441	0.16	1.03
NOAA-14	NIGHT	NLSST	502	0.07	0.84
NOAA-12	DAY	NLSST	374	0.43	1.00
NOAA-12	NIGHT	NLSST	285	0.20	1.07
CoastWatch Great Lakes Region					
Satellite	Time	Algorithm	Number of Matches	(Satellite-Buoy) SST	Standard Deviation
NOAA-14	DAY	MCSST	215	0.38	1.01
NOAA-14	NIGHT	NLSST	157	0.41	0.80
NOAA-12	DAY	MCSST	122	0.26	0.83
NOAA-12	NIGHT	NLSST	78	1.52	1.27

If the center value of the 3 × 3 AVHRR SST array is two standard deviations above or below the nine points mean value, this matchup is not used in the statistics calculation. After we exclude the matchups beyond two standard deviations, the remaining matchups are 1726 for coastal regions and 658 for the GL region, respectively. This means that we include about 95% of the matchups in the original dataset in our later analysis. Significant differences between the center and the mean value may happen when there is a thermal front in the 3 × 3 array or some of the 3 × 3 array points are cloud contaminated. The number of matches, satellite-buoy bias, and its standard deviation are given in Table 2.

5. DISCUSSION AND CONCLUSION

The NOAA/NESDIS operational NLSST SST retrieval algorithm is validated using the matchup data set of NOAA moored buoys and NOAA-12 and NOAA-14 satellite measurement in three US coastal regions and in the Great Lakes in 1997. For the three US coastal regions, the NLSST algorithm NOAA-14 AVHRR SST have a bias and standard deviation of 0.16°C and 1.03°C for daytime, 0.07°C and 0.84°C for nighttime. For NOAA-12 daytime SST, the NLSST gives good result with a bias 0.43°C and a standard deviation of 1.00°C. However, the bias and standard deviation are very large for the NOAA-12 nighttime algorithm (Table 2). In the Great Lake the large bias mostly happened for nighttime. The linear MCSST algorithm gives good results for the Great Lake during the daytime. During mid-May and early July, a large SST bias was observed due to a calibration software error. These data were not included in the validation results. A positive bias is observed over all the validation regions for both NOAA-12 and NOAA-14 satellites. NOAA 14 SST is more accurate than that of NOAA-12.

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